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Themed Collection

Heading towards a renewable energy rich power system

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The Cabinet of Sri Lanka (Decision dated July 27, 2021) approved the commitment of achieving 70% renewable energy in electricity generation by 2030 made under Nationally Determined Contributions (NDC) to the United Nations Convention on Climate Change. Achieving this target leads to operating our power system entirely by renewable energy sources, including 1608 MW of large hydro power plants (saturated from 2025 onwards) and about 400 MW of small hydro power plants, in some periods of the year. This article discusses the practical and pragmatic approach towards integrating a high proportion of renewable energy into our national network.

What are renewable energy sources?

Renewable energy sources are inexhaustible energy sources that do not produce Green House Gasses. Established technologies include wind power, hydro, solar photovoltaic, landfill gas, energy from municipal waste, biomass and geothermal generation. Emerging technologies include tidal stream, wave-power and solar thermal generation. Out of these technologies, wind, solar, energy from municipal waste, biomass and geothermal generation are viable options for Sri Lanka. As municipal waste, biomass and geothermal uses conventional steam power plants, other two technologies are discussed in detail here.

Wind Power

Generating electricity from the wind is one of the most effective and rapidly growing ways of harnessing renewable energy and increasing numbers of wind turbines are being installed in many countries. Modern wind turbines can be very large with rotor diameters greater than 200 m and similar tower heights. Figure 1 shows the rapid growth in the maximum size of commercially available turbines over 30 years. It also compares the size of the wind turbines to the largest aircraft.

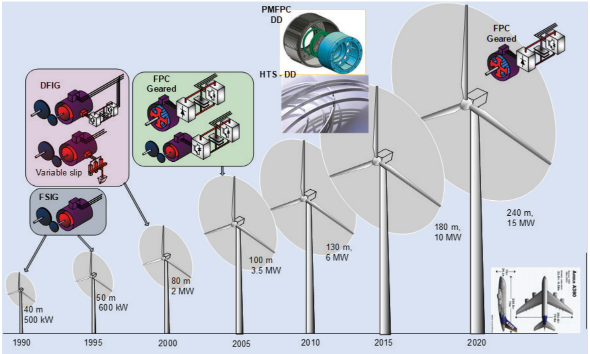


Figure 1: Evaluation of wind turbines

Early designs of electricity generating wind turbines were relatively simple devices in which the speed of rotation of the drive train, and hence of the aerodynamic rotor, was fixed by the generator locking on to the frequency of the grid. This simple design is still used for some turbines up to 2 MW in rating but is not used for modern very large turbines. Figure 2 shows a cross section through the nacelle of a fixed speed wind turbine [1, 2].

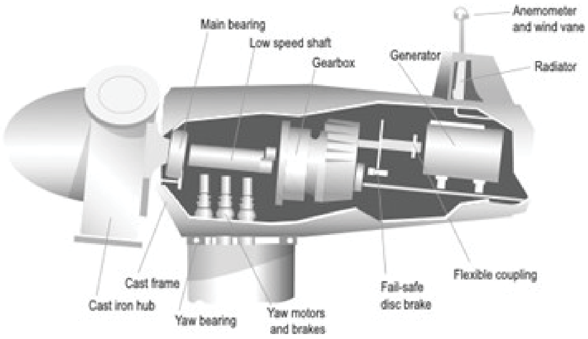


Figure 2: Nacelle of a fixed speed wind turbine [1]

It consists of three blades mounted upwind of the tower and a low-speed main shaft driving an induction generator through a speed increasing gearbox. The blades rotated slowly about their longitudinal axis by an actuator when the wind speed and output power exceed their rated values. The nacelle is mounted on a large, slewing ring yaw bearing at the top of the tower and is orientated into the wind by yaw motors controlled from a wind vane located on top of the nacelle. The wind vane gives a signal showing if the nacelle is not facing directly into the wind. Power is taken from the generator to the bottom of the tower across the yaw bearing by flexible pendant cables that can accommodate two to three rotations of the nacelle. The anemometer that is adjacent to the wind vane is used only to control the starting and stopping of the turbine.

All very large modern wind turbines operate at variable rotational speed and the generator output is connected to the electrical grid though power electronic converters. As wind turbines become larger their structures are increasingly dynamic, using active control to manage the loads through sophisticated control systems. The frequency of the electrical power system (constant at 50 or 60 Hz) determines the rotational speed of any generator that is connected directly to it. Generators manufactured with two magnetic poles always operate at around 3000 rpm on a 50 Hz system, whereas if constructed with four magnetic poles the speed of rotation will be close to 1500 rpm. Conceptually, the simplest way to obtain variable speed operation of a wind turbine is to convert all the variable frequency output of the generator to direct current (dc) and then use an inverter to convert this power to the 50 Hz (ac) of the electrical network. This rectification to direct current and inversion to 50 Hz allows the generator to rotate at any speed and produce electrical energy at any frequency. It de-couples the generator speed from the network frequency. Two power converters are used to connect the generator operating at varying speed and frequency to the 50 Hz of the network as shown in Figure 3 [3].

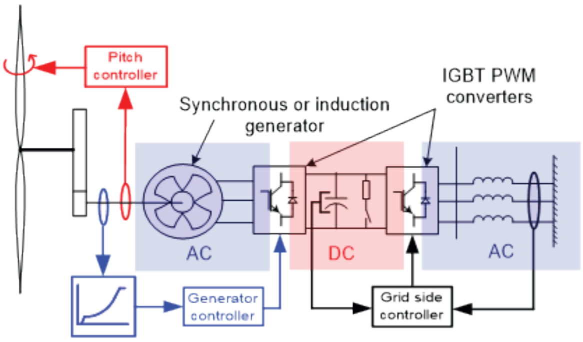


Figure 3: Variable speed operation through Full Power Conversion

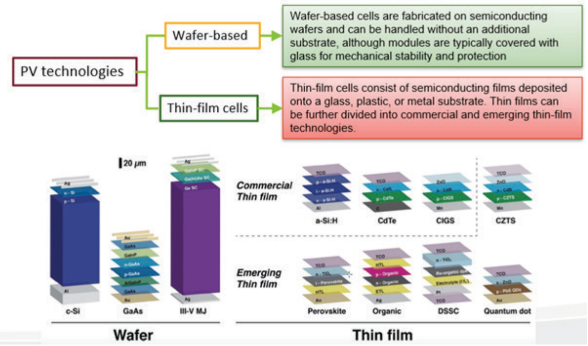
The generator side converter takes the power at the variable frequency from the generator and converts it to dc. The grid side converter inverts the dc to the 50 Hz of the network. Both converters use large transistors, Insulated Gate Bipolar Transistors (IGBTs), in a bridge connection. These IGBTs can be considered as large switches that can be turned on and off very rapidly. The generator converter switches in such a way as always to produce dc while the network converter synthesises a 50 Hz sine wave current that is injected into the grid through the coupling reactors.

Solar PV

Photovoltaic (PV) systems generate electricity directly from the light of the sun and are making an increasingly important contribution to electricity supply in many countries, with a recent rate of growth of the worldwide installed capacity of PV systems of around 20% per year. This rapid growth has been stimulated partly by financial support measures that have been offered by a number of governments as they de-carbonise their electricity supply systems but also because there has been a dramatic reduction in the price of photovoltaic modules with technology development and increased manufacturing volumes.

Most solar panels that are installed today use mono- or poly-crystalline silicon solar cells and are connected to the electricity network. The panels are mounted either on the roofs of buildings or are supported on ground mounted structures in solar farms. Some innovative buildings have photovoltaic modules integrated into their facades or roof. Solar farms are usually located in areas of high solar radiation where land is cheap but are also being constructed in many other parts of the world, including in higher latitudes. Photovoltaic generation also plays an important role in supplying electrical power in remote areas where there is no grid electricity supply.

As well as photovoltaic cells that use wafers of crystalline silicon, cells made from thin film material are offered by several manufacturers. Thin film cells use a small amount of semiconductor material deposited on an inert substrate and have the potential to be cheaper than the thicker bulk silicon cells. There are also exciting new developments of new photovoltaic materials, but these have yet to be deployed widely. The array of solar PV technologies is shown in Figure 4.



Wafer-based cells are fabricated on semiconducting wafers and can be handled without an additional substrate, although modules are typically covered with glass for mechanical stability and protection

Thin-film cells consist of semiconducting films deposited onto a glass, plastic, or metal substrate. Thin films can be further divided into commercial and emerging thin-film technologies.

Figure 4: Solar PV technologies [4]

The output from a photovoltaic system depends completely on the solar energy resource and usually peaks around noon. At higher latitudes the solar irradiance drops in the winter resulting in low-capacity factors and poor utilisation of the photovoltaic equipment. Of course, at night a photovoltaic system produces no output.

Photovoltaic technology is usually considered in three generations.

- The 1st generation technology uses wafers of mono- or poly-crystalline silicon. These bulk silicon devices are produced in large quantities and dominate the commercial market for photovoltaic panels.
- The 2nd generation of technologies uses a thin film of active photovoltaic material on an inert substrate. This generation includes amorphous silicon which is cheaper but less efficient than crystalline silicon and other thin film semiconductor materials such as Copper Indium Gallium diSelenide (CIGS) and Cadmium Telluride (CdTe). All of these technologies are used in the commercial production of flat plate photovoltaic modules. In addition, Gallium Arsenide (GaAs) is used for solar panels in space craft and for concentrating terrestrial systems.
- The 3rd generation includes the emerging technologies of dye-sensitised and organic/polymer solar cells sometimes using Perovskite materials. The principle of operation of these devices differs slightly from first- and second-generation technologies, and third-generation

devices have yet to be produced in large quantities. They are the subject of very active research and development particularly to improve the long-term stability of the materials.

Mono- and poly-crystalline silicon technologies are mature and the cells are encased in robust modules whose output characteristics are well defined and stable. These first generation photovoltaic modules have been shown to work effectively for more than 20 years in harsh conditions with little maintenance. However, the cells are relatively thick (100-200 μm) and so use significant quantities of pure silicon that is both expensive and takes considerable energy to produce. The energy payback time of a solar project is up to five years depending on the solar resource of the site where it is installed.

Figure 5 shows the main functional elements of a grid-connected photovoltaic system. These are the solar modules in an array, a maximum power point tracker and a dc/ac inverter. The dc output of the photovoltaic panels is fed to a maximum power point tracker to extract the maximum power from the photovoltaic cells. The maximum power point tracker stage is a dc/dc converter that varies the voltage applied to the modules to extract maximum power for the ambient conditions. The dc power is then inverted to ac and injected into the power network. The maximum power point tracking function may be implemented within the inverter or in a separate device. A large grid-connected system is likely to have multiple maximum power point trackers and either a large central inverter or multiple smaller inverters.

For most grid-connected PV systems, the grid serves as an infinite energy sink and provides a strong frequency and voltage reference for the operation of the inverter. An inverter for a grid-connected photovoltaic system constantly monitors the condition of the electricity network to which it is connected and only continues to operate if the grid network is in its normal operating condition, i.e. the frequency and voltage are normal. Usually a grid-connected photovoltaic inverter cannot operate in a stand-alone mode and will shut down if the grid loses its supply from the large central generators or if a fault causes a local section of network to become isolated.

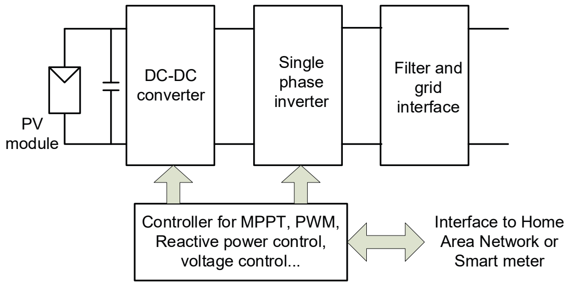


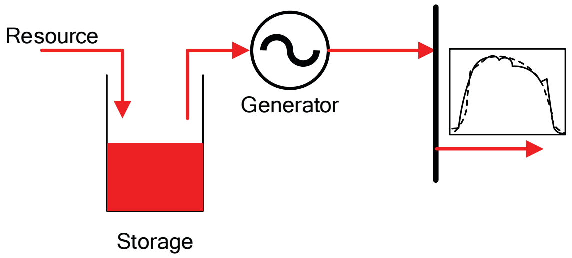
Figure 5: Grid Connection of Solar PV

How is the power system currently operated and how its operation changes with more renewables?

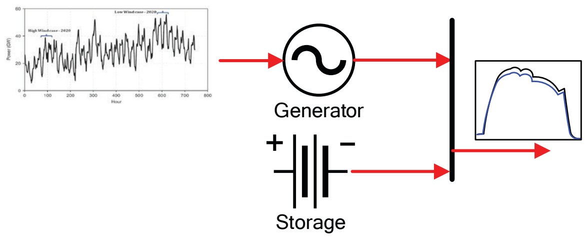
Modern electrical power systems generate power with ratings up to 1000 MW driven by high-pressure steam from fossil fuel boilers and nuclear reactors or by hydro power. The electrical power is fed through generator transformers to a high voltage interconnected transmission network, known as a grid. The transmission system is used to transport the bulk electrical power, sometimes over considerable distances, and it is then extracted and passed down through a series of distribution transformers to radial distribution circuits for delivery to the customers.

One key attribute of fossil fuels used to generate electrical energy centrally by the generation of electricity in large power stations is their high energy density. They can be transported easily by truck or pipeline and converted in devices occupying a small volume. In contrast, renewable sources of energy are significantly less dense, and the resource must be exploited where it occurs.

A second important characteristic of fossil fuels, that is shared by large reservoir hydro, is that energy can be stored for long periods with little degradation. Fossil fuels store energy in a dense form and this, most useful attribute, has allowed the conventional electrical energy system to be developed in its present architecture where electrical energy demand is unconstrained and supply is arranged always to meet it. It is unlikely that a future mainly renewable energy system can be built and operated cost–effectively without at least some of the energy demand being controlled in response to variations of the renewable resource. Unless expensive energy storage is used, renewable sources have to be converted into electrical energy when the resource is available. Figure 6 depicts the operation of the conventional power system and the future power system having a large penetration of renewables.



Today: Generation follows the load



Future: Load minus storage follows the generation

Figure 6: Conventional and future power system

The generating units are mainly synchronous machines. Synchronous generators are analogues to a dancing group who does Zumba or acrobatic dancing. These dancers are following their steps tuned to a music that are at different frequencies. All the synchronous generators connected to the grid (irrespective of their location) are tuned to 50 Hz frequency and act together, as dancers in a dancing group, for any changes in the grid frequency. At any given time, the total power generated by the synchronous generators are equal to the total load connected, thus the grid operates at 50 Hz. If there is an imbalance between generation and load demand that will reflect on the system frequency. In terms of frequency, an electric power system can be viewed simply as a single rotating mass of equivalent inertia. All the turbine generators and spinning loads operate as a single coherent generator with one rotational speed and a single system frequency. The equivalent inertia is the sum of the inertias of all the turbines and generator rotors that are connected to the power system. This inertia plays a vital role when keeping the frequency within its operational limits, especially under contingencies. When renewable energy generators are connected to the system, they displace conventional power plants, and the system inertia drops resulting in more rapid frequency excursions for changes in generation or load. This reduction in the inertia of the power system caused by increasing operation of renewable generators is a major topical concern of power system operators.

The electrical demand of a power system changes continuously. At any time only some generators are in use to maintain the balance between the demand and generation. Other units are held in reserve to meet increasing load and be ready in case a generator breaks down. Generators are called on to operate depending on their cost of operation and maintenance and fuel as well as the need for reserve capacity. The arrangement through which this control of generators is known as scheduling. Scheduling is based on the economics and technical requirements. For example, the coal power plant which is economical to operate and inflexible is scheduled to be operated whole day whereas hydro power plants are used to take the varying load during a day.

Even in a power system without a significant proportion of renewable generation mismatches between the scheduled generation and demand are inevitable. These are due to variations in customer demand, sudden connection or disconnection of large loads, sudden loss of part of the transmission network due to a fault, and sudden loss of a large generator. Any mismatch between the generation and load results in a frequency change that is compensated initially by the kinetic energy of rotating generators. Minor mismatches between customer demand and generation are compensated automatically by the action of the governors of large generators. When renewable generators are in operation, mismatches between generation and loads are also caused by the variability of the generation.

The stability of the conventional power system is provided by the large synchronous generators. As discussed before, these units adjust their output to ensure there is a balance between system demand and supply at all times. They also provide the majority of the system inertia. Most renewable generators do not take part in the balancing of the system but merely supply energy from the wind or sun when the resource is available. These renewable generators can only operate when there is a strong voltage and frequency reference provided by the large synchronous generators.

It is clear that operating renewable generators as sources of energy only and relying on the large synchronous generators to provide all the control and stability of the power system is only satisfactory when there is a modest fraction of generation from renewable sources. As more and more renewable generation is connected to the power system this simple way of operation will have to change and the renewable generators must evolve to contribute fully to the control and stability of the power system.

What are the changes required to operate a Power System with a large penetration of renewables?

As discussed in previous sections, the variation and intermittency of the power output of conventional renewable energy generators cause operational difficulties and incurs additional costs to Grid operators and finally to electricity consumers. A Grid Operator (such as CEB) is responsible to maintain uninterrupted power supply at a reasonable tariff with defined parameters in power quality. At present the operational difficulties caused by intermittency and variability of the renewable generators are countered and managed by connecting into a large power system, where renewable generators benefit from the diversity of the loads, the inertia of main generators, and the stored energy in the fossil fuel of conventional generators. In some cases, in order to maintain power system stability certain selected large fossil fuel generators are operating in standby mode.

In principle an energy storage device can be installed along with a renewable generator to smooth the output or to store energy so as to supply energy when renewable resource is not available. To provide long-term energy storage options like batteries, fuel cells, or pumped hydro could be used. Worldwide, there have been number of examples of the demonstration of energy storage system with a renewable generator. For example, a NaS battery system of 245 MWh, 34 MW has been installed at the 51 MW Rokkasho wind farm in Japan to smooth the wind power output and to allow the wind farm to supply demand according to a defined schedule. This is shown in Figure 7.

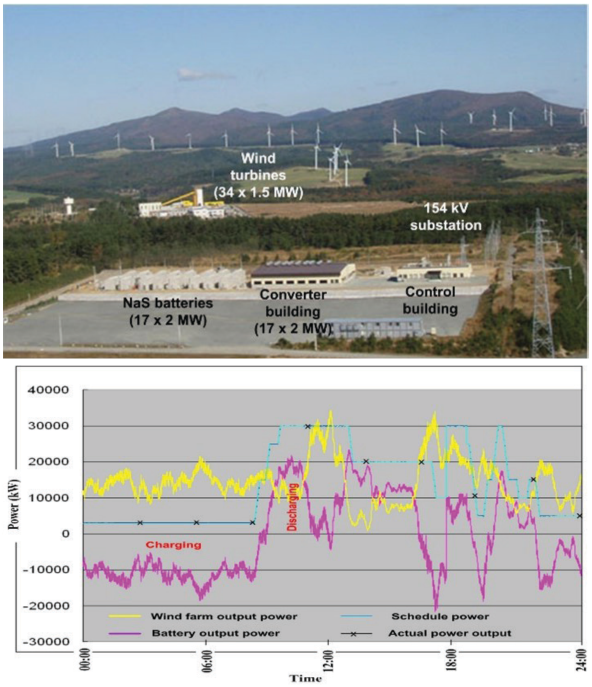


Figure 7: Application of energy storage system for a wind farm

It would appear to be desirable to install an energy storage device with every renewable generator, but this is not common practice. The initial capital cost of energy storage devices remains high and the maximum achievable overall efficiency of storing and retrieving electrical energy is only around 80%. However, the prices of the energy storages are coming down rapidly and many applications with practical solutions are emerging. This will enable power grid operators to absorb higher proportion of renewable energy sources.

For a country like Sri Lanka, pump hydro is one of the viable energy storage options. These schemes have two reservoirs one at a higher elevation than the generator-pump station and the other at a lower elevation. During the time solar or wind generation is high, water can be pumped from the lower reservoir to the higher reservoir. In the peak house, the water stored in the higher reservoir can be used for power generation.

Intelligently controlled active networks that facilitate the integration of renewable generation into the power system are also being considered widely. There are a range of enabling technologies such as information and communications technologies; sensing, measurement, control and automation technologies; power electronics; and advanced components and materials that facilitate intelligently controlled active networks. The name smart grid has become common to describe the future power network that will make extensive use of the above-mentioned technologies to support a flexible, secure and cost-effective de-carbonised electrical power system.

A de-carbonised electrical power system supplied from renewable energy sources and generators with steady power output (perhaps nuclear and fossil plant with Carbon Capture and Storage), needs greater involvement and status of customer end load in its pattern of operation. Hence the concept of 'Demand Side Participation' has emerged in power grids worldwide. Demand Side Participation is a potential means of increasing flexibility and controllability in the power system. Controllable loads such as charging electric vehicles will allow increased utilisation of renewable energy effectively. More radically, it is anticipated that the battery energy storage of electric vehicles may be used to inject power into a localized grid at times to replace part of high-cost power generation and to facilitate islanded operation of distribution electrical networks. The role of smart metering and how the customers will wish to control their loads at a given time and their willingness to take part in the operation of a power system is an important topic and there are studies and investigations with trials are being undertaken currently in many countries.

Concluding Remarks

Sir Lanka and many countries around the world are adding more and more renewable energy sources to decarbonize their electricity energy infrastructure. However, it is important to consider the following points before deployment of large-scale renewables.

- Identification and evaluation of standard operational philosophy, processes, practices and control room tools.
- Development of dynamic scheduling systems to accommodate system changes arising due to variable renewable energy sources.
- Development of energy storage solutions to overcome intermittency and variability of renewable energy sources. On this regard, the immediate implementation of possible pump-hydro schemes is important.
- Development of technical solutions and methods to overcome decrease in system inertia with the higher penetration of renewables.
- Development of grid connection codes that demand asynchronous generators associated with renewable energy sources to match the contributions (technical nature) offered by typical synchronous generators.
- Committed plan to accommodate renewables in structured development phases along with technology advancement.
- Establish a regulatory policy on electricity tariff and incentives that enables demand side participation and empowerment.

More importantly, continuous research and development activities with the involvement of utility, network operators, economics, technical solution providers, academics, and researchers should be considered to take our power gird towards a decarbonised and sustainable smart grid.

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